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(19)

(11) Publication number: 0 221 560 A2

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 86115406.0

(22) Date of filing: 06.11.86

(51) Int. Cl.4: G 02 B 6/34
H 04 B 9/00, G 02 F 1/01

(30) Priority: 06.11.85 US 795482

(43) Date of publication of application: 13.05.87 Bulletin 87/20

(84) Designated Contracting States: DE FR GB NL SE

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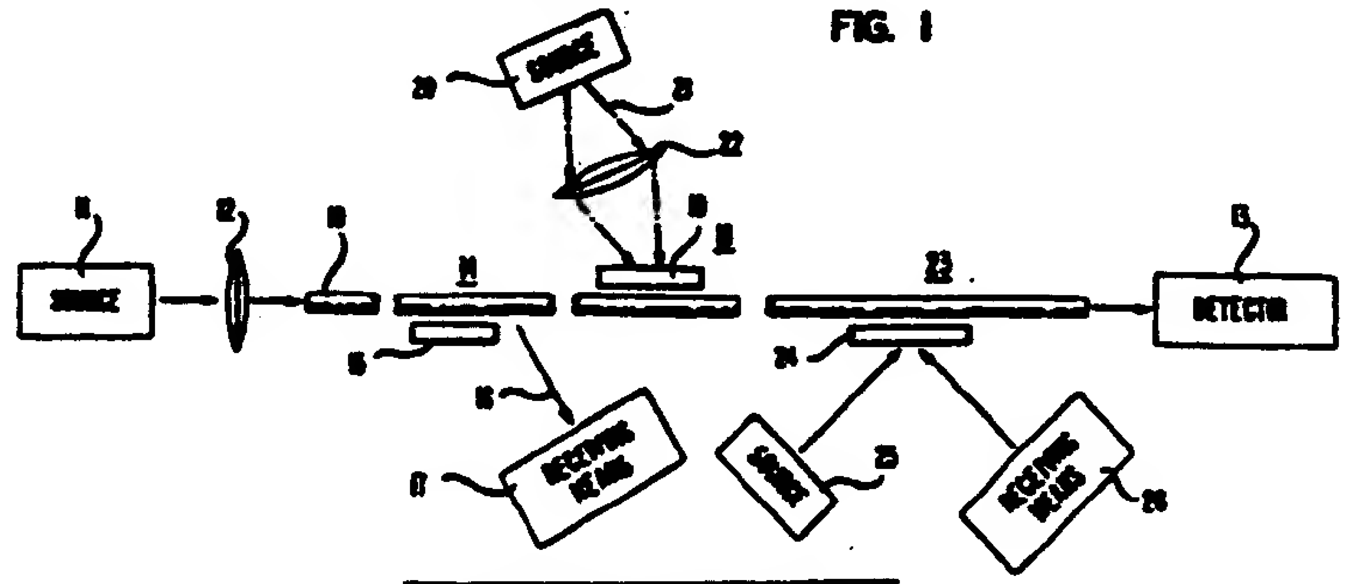
(54) Coupling device for single mode optical fiber and communications system comprising same.

(57) Optical radiation can be efficiently removed from, or injected into, single mode optical fiber at an intermediate point along the fiber, by causing quasi-resonant coupling of the guided mode LP_{01} to an appropriate tunneling leaky (TL) mode, e.g., LP_{11}. Such coupling is caused by means of a "grating" in the fiber, with the grating being formed by impressing a periodic (or pseudo-periodic) modulation on the fiber, or by causing a periodic (or pseudo-periodic) variation of the refractive index of the fiber by means of the photoelastic or the photorefractive effect. The nominal grating spacing $\Lambda(z)$ is chosen such that

$O_o = (2\pi/\bar{\Lambda}) > \beta_{01} - 2\pi n_{cl}/\Lambda_o$, where $\bar{\Lambda}$ is the average grating spacing, β_{01} is the propagation constant of the LP_{01} mode, n_{cl} is the refractive index of the fiber cladding, and $_o$ is the wavelength of the radiation to be coupled from or into the fiber. Furthermore, $\Lambda(z)$ is to be chosen such that

$O_o\ \beta_{01} - \beta_{rs}$, where β_{rs} is the propagation constant of the selected TL mode. In order for the coupling to be quasi-resonant, it is necessary that α_{rs}, the attenuation constant of the selected TL mode, be relatively small, typically < 1 dB/cm. By appropriately choosing $\Lambda(z)$ and/or the amplitude function of the grating, it is possible to increase the coupling efficiency above what is possible with a constant spacing, constant amplitude grating. Devices according to the invention can be advantageously used not only as radiation couplers but also as filters and, if they are of the photorefractive type, as amplitude modulators.

FIG. 1



EP 0 221 560 A2

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COUPLING DEVICE FOR SINGLE MODE OPTICAL FIBER AND COMMUNICATIONS SYSTEM COMPRISING SAME

Field of the Invention

This invention pertains to devices for coupling optical power from and/or into optical fiber, and to optical fiber communication systems comprising such devices.

Background of the Invention

Optical communications has undergone very rapid development, to the point where optical fiber transmission systems are becoming almost commonplace. Optical fiber is not only used for trunk (i.e., long-haul) applications, but also to transfer information over short distances, e.g., in local area networks, and potentially, in the subscriber loop.

In many applications it is necessary, or at least desirable, to inject optical power into a fiberguide at intermediate locations, and/or to extract optical power from the fiberguide at such locations, without the need for breaking or terminating the fiberguide, and without requiring special preparation f the coupling point in the fiberguide. Such couplers have been known in the art for some time. See, for instance U.S. Patent 3,931,518, ('518), which teaches a particular embodiment of a coupler type which will herein be referred to as a "grating" coupler.

The '518 patent teaches that optical power can be coupled from an optical fiber by impressing a periodic deformation onto the fiber, with the periodicity of the deformation chosen such as to induc coupling between appropriate modes of radiation. In this fashion power can be transferred resonantly from lower to higher order guided or bound modes, and

nonres nantly from the higher b und m des to th so-called tunneling leaky (TL) modes, which ar then removed from the cladding of the fiberguide with the aid of a dielectric body that is in contact with the fiberguide at a point downstream from the periodic deformation region and which has a refractive index which is approximately equal to or greater than the index of refraction of the cladding.

For an exposition of the relevant theory, see, for instance, D. Marcuse, Theory of Dielectric Optical Waveguides, Academic Press, 1974, especially pages 95-157. Briefly, it can be shown that it is possible to provide a coupling mechanism in multimode fiber such that the (i, j)'th and (p, q)'th bound modes are coupled to produce complete energy exchange over a coupling length $L_c = \pi/R_{ij,pq}$, where the coupling constant $R_{ij,pq}$ depends upon fiber parameters such as the core radius, the refractive index difference between core and cladding, the operating wavelength, the fiber profile shape, and, in a coupler as disclosed in '518, on the amplitude of the distortion of the fiber. As the distortion amplitude increases, the coupling length L_c decreases. Thus, a prior art coupler as disclosed in '518 can be tuned for maximum efficiency by adjusting the amplitude of the distortions of the multimode fiber, to result in resonant energy transfer from low to higher order bound modes.

Although '518 teaches that optical power can be coupled from the single guided mode (usually referred to as the LP_{01} mode) of single mode fiber to one or more of the TL modes of such fiber, and that, therefore, couplers of the type disclosed in '518 could be used not only with multimode fiber but also with single mode fiber, this type of coupler has in fact only been used in conjunction with multimode fibers. The reason for this is as follows. It is generally underst od in the

art that th coupling proc ss b tween bound modes in multimode fiber is a res nanc process, and that c nsequently the coupling parameters can be adjusted to result in efficient resonant power transfer into high order bound modes, and from there nonresonantly into TL modes. On the other hand, the theory teaches that, in single mode fiber, the coupling between LP_{01}, the bound mode, and a TL mode, e.g., LP_{11}, is nonresonant, such that the radiation amplitude in LP_{01} decreases exponentially with distance along the propagation direction, due to the continuous transfer to the TL mode of a constant fraction of the power in LP_{01}. See, for instance, page 112 of the above cited book by Marcuse, where it is stated that, for the case of a single-mode guide, the power coupled into TL (radiation) modes is radiated from the guide and does not interact with the guided mode. Since such nonresonant coupling cannot be tuned to result in efficient power transfer between LP_{01} and TL modes, it is generally accepted in the art that fiber taps of the "grating" type cannot be made to function efficiently in single mode fiber.

The fact that microbending-induced mode coupling in multimode fibers can involve a resonance mechanism has also been used to construct highly sensitive fiber optic displacement sensors. See, for instance, N. Lagakos, Digest of Technical Papers of the Conference on Optical Fiber Communication, New Orleans, La., January 1984, pp. 56-58.

G. F. Lipscomb et al, First International Conference on Optical Fiber Sensors, London, April 1983, pp. 117-121, report on the result of experiments with single mode and multimode optical fiber, in which a single bend was induced in the fiber by bending the latter around a cylindrical mandrel. Interference effects between bound modes and TL modes were observed in both types of fiber. In particular, it was observed that th b nding caus s som of th core-mode power to

convert into the cladding-mod power and, at specific angles, some of the cladding-mode pow r t convert back into core-mode power. It will be noted that the interference effects in the single-bend configuration of Lipscomb et al are not the desired resonance coupling effects that are of concern in this application. In this respect, see also pages 156-157 of the above cited book by Marcuse.

K. P. Jackson et al Applied Physics Letters, Vol. 41(2), pp. 139-141 (1982) report on a tapped single mode optical fiber delay line. The taps were formed by urging a tapping pin against the fiber, thereby inducing a 1.5 mm bend radius in the fiber. No resonant coupling is involved in this technique.

Since single mode optical fiber is rapidly becoming the fiber type of choice for long distance transmission, and is considered to be a promising medium even for short-haul applications in which a multiplicity of sending and/or receiving stations are connected by a single or dual fiber transmission path, it is clear that it would be very desirable to have available efficient means for coupling optical power into, and/or out of, single mode optical fiber without breaking the fiber and without permanently changing the characteristics of the fiber in the coupling region. This application discloses such coupling means.

Glossary of Terms

An "optical fiber" (or fiberguide, or other equivalent term) is an elongated body comprising an interior region (the core) having a higher refractive index (at the signal wavelength λ_0) than the region surrounding the core, the cladding. Optical fiber can comprise cladding having a multiplicity of regions differing from each other with respect to the refractive index, and typically is enveloped by a coating, or multiple c atings. Th c ating typically is a polymer and may be transparent (and in fib r used in practicing

th inventi n typically is transparent) to th radiation coupled into r from th fiber.

In optical communications systems frequently two or more lengths of fiber are spliced or otherwise joined together to form a continuous optical transmission path from a first fiber end to a second fiber end. One end often can be considered to be the input end and the other the output end of the transmission path. However, it is possible to operate a system such that a given path carries signals in both directions, with sending and receiving means at each fiber end.

The radiation guided in an optical fiber, or radiated therefrom, can be described in terms of "modes" of radiation. Herein the nomenclature introduced by D. Gloge, Applied Optics, Vol. 10, pp. 2252-2258 (1971) is used to identify the modes. With each mode LP_{ij} can be associated an attenuation constant α_{ij} and a propagation constant β_{ij}.

"Tunneling leaky" (TL) modes in single mode fiber are the low order radiating modes (LP_{11}, LP_{12}, LP_{21},....) that have relatively small attenuation constants.

"Coupler" herein refers both to means for extracting optical power from an optical fiber at an intermediate fiber location, and to means for injecting optical power into an optical fiber at an intermediate fiber location.

A "grating" herein is an intermediate fiber region in which the transmission characteristics of the fiber are varying in a periodic or pseudo-periodic fashion. A grating comprises N elements, with repeat length $\Lambda(z)$, where z is the longitudinal fiber coordinate. Associated with the grating is an "envelope amplitude" described by an "envelope" function g(z) that can b a constant or vary as a function f z. Th fiber charact ristics vary in a "peri dic" manner if $\Lambda(z)$ is a

constant, and they vary in a "pseudo-p riodic" mann r if $\Lambda(z)$ is a r gular and predet rmin d function of z. Th "amplitud " of an element of a grating is th maximum fiber axis displacement, or the maximum refractive index change, associated with the element.

Summary of the Invention

The invention comprises means for efficiently coupling electromagnetic radiation of wavelength λ_o into or from an intermediate part of a single mode optical fiber, i.e., without breaking or terminating the fiber, and typically without permanently modifying the transmission properties of the fiber, e.g., by removal of all or part of the cladding material at the coupling location. The coupling means comprise means for forming a grating, e.g., means for locally changing the optical characteristics of the fiber by impressing a multiplicity of regularly (periodically or pseudo-periodically) spaced deformations on the fiber, or by changing the refractive index of the fiber in a multiplicity of regularly spaced fiber regions. In a coupling device according to the invention the grating spacing $\Lambda(z)$ is chosen such that

$\Omega_o = (2\pi/\bar{\Lambda}) > \beta_{01} - 2\pi n_{cl}/\lambda_o$, where $\bar{\Lambda}$ is the average repeat spacing, β_{01} is the propagation constant of the LP_{01} mode in the fiber, and n_{cl} is the refractive index of the fiber cladding. Furthermore, in such a device according to the invention the grating spacing $\Lambda(z)$ is chosen such that $\Omega_o \quad \beta_{01} - \beta_{rs}$, where β_{rs} is the propagation constant of a TL mode LP_{rs} in the fiber. This choice of repeat distance can result in quasi-resonant energy transfer between LP_{01} and LP_{rs} (and adjacent modes), provided the power loss from LP_{rs} is small over the distance $N\bar{\Lambda}$. A typical upper limit on the attenuation constant α_{rp} of the LP_{rp} mode is about 1 dB/cm.

Th grating can be produced by any appr priat means, including by urging ne, r a pair of, suitably corrugated bodies against the fiber, thereby impressing deformations on the fiber, or by appropriately changing the refractive index of the fiber, for instance by means of the photorefractive or of the photoelastic effect.

The grating can have constant amplitude, or the amplitude can be a function of z. Furthermore, the grating can be periodic, i.e., with Λ being constant, or it can be pseudo-periodic, with the repeat spacing being a function of z. Appropriately shaped nonconstant amplitude may result in improved coupling between the fiber and an external radiation detector or radiation source, as will be described in detail below. Use of pseudo-periodic gratings may, inter alia, result in a coupler having enhanced frequency dependence. Such a coupler may, inter alia, be useful as a notch filter. The "shaping" of the grating to thereby increase coupling efficiency, frequency response, or other device characteristic, is considered to be a significant aspect of the invention.

Due to the fact that devices according to the invention can be made to be highly wavelength selective, such devices are considered to be potentially of utility as wavelength-dependent couplers in wavelength division multiplexed systems, or in Raman amplified soliton systems. Devices according to the invention are also potentially useful as notch filters, as photorefractive modulators, or as variable attenuators. Attenuators according to the invention possess a highly advantageous feature not typically found in prior art attenuators, namely, they do not cause power to be reflected back to the radiation source. Such reflection may affect the emission characteristics of sensitive sources and thus is undesirable. Furthermore, gratings according to the invention can be used in temporary taps such as are fr qu ntly r quired f r repair or reconfigurati n

purposes. In such cases, the grating can advantageously be incorporated into a clamp-on device. Such devices can be used with coated or buffered individual fiber as well as with laminated ribbon fibers.

Disclosed is also an optical fiber communications system comprising a source of radiation of wavelength λ_o, a single mode optical fiber, means for coupling the radiation into the fiber at a first fiber location, means for detecting the radiation, after its transmission through the fiber, at a second fiber location spaced apart from the first location, means for coupling radiation (of wavelength λ_o, or possibly of wavelength $\lambda \neq \lambda_o$) into and/or from the fiber at a third fiber location intermediate the first and second locations, with the coupling means being of the type described above. The system optionally may comprise couplers according to the invention used as attenuators, filters, or modulators.

Brief Description of the Drawings

FIG. 1 schematically shows an exemplary fiberguide communications system comprising means for injection and extraction of optical power at intermediate fiber regions;

FIG. 2 depicts schematically the axis of an optical fiber with periodic distortions that form a "grating" of constant amplitude;

FIG. 3 is a plot of the Fourier transform of the grating function $f(z) = A\cos\Omega_o z$, $(-\pi N/\Omega_o) < z < (\pi N/\Omega_o)$;

FIG. 4 is a plot of the grating function $f(z) = g(z)\cos\Omega_o z$, for the same range of z as in FIG. 3, where $g(z) = \exp(-z^2/a^2)$;

FIG. 5 depicts the Fourier transform of the function shown in FIG. 4;

FIG. 6 sh ws the radiation pattern of an exemplary semiconductor laser and th acc ptance functi n of an exemplary single mode fib r;

FIG. 7 schematically shows an exemplary c mmunicati ns system comprising a photorefractiv modulator; and

FIG. 8 schematically depicts a photorefractive modulator.

Detailed Description

FIG. 1 schematically depicts an exemplary communications system according to the invention, in which 10 is a length of optical fiber, 11 a source of electromagnetic radiation, e.g., a laser emitting at 1.55 μm, 12 means for coupling the radiation into an end of the fiber, and 13 is a radiation detector. Intermediate locations 14, 18, and 23 are sites at which coupling means according to the invention are deployed, with 15 being means for tapping radiation 16 from the fiber, 19 being means for injecting radiation 21 into the fiber, and 24 being means for both tapping and injecting of radiation. Receiving means 17 and 26 can be any means for receiving the tapped radiation, e.g., a detector, or another fiber. Similarly, sources 20 and 25 can be any source of radiation to be injected, e.g., a laser, a LED, or another fiber. Although means 22 for changing the shape of the radiation pattern are shown at only one coupling site, it is clear that such means can, but need not be, used generally.

A central aspect of the instant invention is the discovery that it is possible to achieve essentially resonant coupling between the propagating mode LP_{01} and TL modes, principally LP_{11}, in single mode optical fiber. This discovery, which is not predicted by currently accepted theory, makes possible the construction of very efficient means for coupling radiation from, and/or into, single mode optical fiber at intermediate points along the fiber, without having to break or terminate the fiber.

If the loss of optical power from a TL mode in a fiber length of the order of a centimeter is only a small fraction of the power in the mode, then the radiation mode acts locally essentially as if it were a bound mode. That is to say, if the quantity $N\Lambda\alpha_{rs} << 1$ for the TL mode LP_{rs} then the power transfer between LP_{01} and LP_{rs} can be essentially resonant. Under these circumstances, coupling conditions (e.g., grating spacing $\Lambda(z)$, number of elements N, and amplitude of the envelope function g(z)) can be found such that the radiation can be efficiently coupled into, or from, a single mode optical fiber. Although useful coupling may also be possible if the LP_{rs} mode attenuation constant is greater than about 1 dB/cm, we currently consider 1 dB/cm to be a realistic upper limit of the permissible attenuation of the selected TL mode or modes.

Many currently used single mode fiber designs are such that, at the design wavelength λ_o of the fiber, the lowest order TL mode (LP_{11}) has a relatively small attenuation constant α_{11}, such that the above discussed limitation generally can be met at least for LP_{11}, and typically also for other TL modes.

As previously discussed, mode coupling is produced by means of a "grating" introduced into the fiber at or near the location where optical power is to be injected into, or removed from, the fiber core. The TL mode LP_{rs} to which LP_{01} couples most strongly is selected by appropriate choice of grating parameters, principally of the repeat distance $\Lambda(z)$ for a given wavelength. By choosing $\Lambda(z)$ such that

$\Omega_o = (2\pi/\Lambda) > \beta_{01} - (2\pi/\lambda_o)n_{cl}$ one insures that LP_{01} couples to one (or more) TL modes. By furthermore choosing $\Lambda(z)$ such that $\Omega_o = \beta_{01} - \beta_{rs}$ the grating causes quasi-resonant coupling principally between LP_{01} and LP_{rs}, if $N\Lambda\alpha_{rs} << 1$. An exemplary value for Λ is of the order of 500 µm. Typically, the grating repeat

distance in single mod fib r is l ss than ab ut 1 mm, which is to b contrasted with the situati n in multim de fiber, where the repeat distance typically is greater than 1 mm.

For realistic gratings in typical single m d fiber, the resonance is of finite width. By this is meant that, for $\Omega_o = \beta_{01} - \beta_{rs}$, coupling occurs not only between LP_{01} and LP_{rs}, but also, albeit weaker, between the former and TL modes LP_{ij} whose propagation constant is close to β_{rs}. In particular, for an N-element grating one can show that a measure of the resonant coupling width is $\Omega_o N^{-1}$, i.e., resonance coupling will occur to modes LP_{ij} if $\beta_{rs}-\beta_{ij} < \Omega_o N^{-1}$.

The required repeat distance for a given fiber can either be determined by computing the propagation constants for the relevant modes by known methods, r it can be determined experimentally. Frequently, it will be found advantageous to use a combination of the tw approaches. As is well known, the value of the propagation constant of a given mode depends not only on the wavelength of the radiation but also on fiber parameters, including effective refractive index and index profile shape.

In order to characterize a grating, it is not only necessary to specify the repeat distance but also further parameters, including the envelope function. For instance, for a grating formed by spatially periodic distortions of the fiber, the envelope function specifies the amplitudes of the distortions impressed on the fiber axis. For a grating formed by spatially periodic variations of the refractive index of the fiber, the envelope function typically specifies th maximum refractive index of the various grating elements.

In a simple exemplary case, the grating is sinusoidal, i.e., it can be described by a function $f(z) = A\cos\Omega_o z$, for $(-\pi N/\Omega_o) < z < (\pi N/\Omega_o)$, and zer

otherwise. The c ordinate origin has be n sel cted such that th grating is symm trical about the c ordinate origin. This is done for the sake of convenience only, and has no fundamental significance.

This function is depicted in FIG. 2, with greatly exaggerated ordinate. In the above exemplary case the envelope function is a constant (A) independent of z. In general, however, the envelope function can be a function of z, and, as will be discussed next, gratings with nonconstant envelope can advantageously be used in devices according to the invention.

As is well known, the radiation pattern from a diffraction grating is described by the Fourier transform of the grating function. Similarly, the pattern of radiation emitted from a fiber that comprises a grating as discussed herein is proportional to the Fourier transform of the envelope function. Since reciprocity applies to the inventive devices, it can immediately be asserted that the Fourier transform of the envelope function also corresponds to the pattern of radiation that can be injected into the fiber by means of the grating. The Fourier transform $F(\Omega)$ of a function $f(z)$ is defined as follows:

$$F(\Omega) = (1/2\pi) \; f(z)\exp(i\Omega z)dz.$$

By way of illustration, if a grating is described by

$$f(z) = A\cos\Omega_o z,$$

for $(-\pi N/\Omega_o) < z < (\pi N/\Omega_o)$, then

$$F(\Omega) = \frac{\sin[N(\Omega-\Omega_o)/\Omega_o]}{(\Omega-\Omega_o)} - \frac{\sin[N(\Omega+\Omega_o)/\Omega_o]}{(\Omega+\Omega_o)}.$$

A graph of the first term of this expression is shown in FIG. 3, and c rr sponds closely t $F(\Omega)$, sinc the second term d s not produce a significant effect.

Th Fourier transf rm of a grating function is related t th radiation pattern in th cladding of th fiber through the expression

$$\theta_{ij} = \cos^{-1}(\lambda_o\beta_{ij}/2\pi n_{cl}), \qquad (1)$$

with the relative radiation amplitude in the directi n that makes an angle θ_{ij} with the undistorted fiber axis being proportional to the amplitude of the Fourier transform for $\Omega = \beta_{01} - \beta_{ij}$. The radiation pattern outside of the fiber can be derived from the pattern in the cladding by a simple application of Snell's law, as will be understood by those skilled in the art. It will also be understood that, in the case of a grating that has a symmetry plane that contains the axis of the fiber, the radiation pattern is symmetrical about the same symmetry plane.

Under appropriate circumstances the coupling efficiency to an external radiation source (e.g., a laser, a LED, or another optical fiber) or a radiation receiver (e.g., a photodetector diode, another fiber or other optical waveguide, including a planar optical waveguide) can be increased by choice of grating shape (e.g., amplitude g(z)). In particular, it is advantageous to form a grating such that the Fourier transform of the grating function f(z) approximates the radiation pattern of the external source or the aperture function of the receiver. This is illustrated in FIGS. 4 and 5, which schematically show an exemplary grating with nonconstant (Gaussian, i.e., $g(z) \quad \exp(-z^2/a^2)$) amplitude and the Fourier transform of the grating function, respectively. The Fourier transform is to be compared with FIG. 6, in which curve 60 is the exemplary radiance distribution of a semiconductor laser, and curve 61 is the output pattern of an exemplary single mode fiber. The close match between th shape of a peak of the F uri r transform (FIG. 5)

and th shape of the curves of FIG. 6 is apparent, indicating the close possible matching between thes sources and a coupler of Gaussian amplitude.

The pseudo-periodic grating function $f(z)$ $[J_1(\Omega_B z)/z]\cos(\Omega_M z)$ has the Fourier transform

$F(\Omega) = [1-(\Omega-\Omega_M)^2/\Omega_B^2]^{1/2}$ for $-\Omega_B < (\Omega-\Omega_M) < \Omega_B$, and $F(\Omega) = 0$ for $\Omega-\Omega_M > \Omega_B$. In these expressions, $J_1(\Omega_B z)$ is the well known first order Bessel function, $\Omega_M = 2\pi/\Lambda_M$, where Λ_M is the central grating spacing, and Ω_B is a constant that determines the width of the Fourier transform. A grating that is described by the above grating function is particularly advantageous as a notch filter, since it will pass unattenuated all wavelengths of radiation, except those in a narrow spectral range.

As expressed by the principle of reciprocity, couplers according to the invention have identical radiation pattern and aperture function. Thus the curv of FIG. 5 also represents the radiation pattern of the coupler used as a tap. Similarly, curve 61 of FIG. 6 corresponds also to the aperture function of a single mode fiber. Thus it is possible to closely match an inventive coupler to a single mode receiving fiber. Frequently it is advantageous to alter the beam width by means of a lens or lenses, for instance, when coupling into the end, or from the end, of a single mode optical fiber.

As mentioned above, a method for forming a grating in a fiber is to mechanically distort the fiber, such that the axis of the fiber assumes the appropriat shape, i.e., as described by the grating function. Means for achieving this are known. See, for instance, U. S. Patents 3,931,518, 4,135,780, and 4,253,727. For instance, two corrugated metal, glass, ceramic, or plastic plates can be urged against the fiber, with the c rrugations aligned to achi ve a periodic fiber axis

distorti n.

An ther possibl m thod for pr ducing a grating in the fiber is the application of a spatially periodic stress to the fiber to induce a periodic variation in the refractive index via the photoelastic effect. Such a stress can be produced by means similar to those used for producing the axial distortion. In the case of grating-formation by axial distortion, it is typically not required to remove the fiber coating, whereas in the photoelastic case, at least with silica-based fiber, the necessary stresses are such that we currently consider it preferable to remove the fiber coating. However, the invention can be practiced with other than silica-based fibers, and other materials, e.g., plastics, can have a substantially larger photoelastic coefficient than SiO_2, and therefore require smaller stresses.

Another method for forming the grating uses the photorefractive effect. The presence of an appropriate dopant (e.g., Fe or Bi) in the fiber core can result in a change of refractive index upon exposure of the fiber to light of appropriate wavelength. For instance, exposing Bi-doped silica to radiation of wavelength of about 568 nm is expected to produce a change in the refractive index of the exposed region.

The photorefractive method avoids the possibility of mechanical damage to the fiber, and offers the potential for forming a grating with time-dependent parameters. Such a grating can be used to modulate the amplitude of radiation guided in the fiber, by time-dependent removal of radiation from the fiber. Such a device can be used, for instance, on customer premises, to provide economical means for modulating an inexpensive cw light source. A portion of an exemplary communications system incorporating such devices is schematically d picted in FIG. 7, wher in 70 c rresp nds to a teleph ne central offic r oth r major switching

center c nnected by trunk lin s 71 to other similar centers. Multiplexed ptical pulses are transmitted over optical fiber lines 72 from and to local distribution points 73, of which only one is shown. Signals arriving in 73 from 72 are demultiplexed and distributed to subscriber lines 74 and transmitted to subscriber stations 75 (only one is shown). The subscriber apparatus typically would comprise a directional coupler 76 if 74 is used as a two-way transmission path. However, no such coupler may be necessary if 74 is a duplex line. In either case, signals arriving in 75 are detected by detector 77, whose output 78 is available for processing by known means. The station apparatus also comprises a cw light source 81 (e.g., an LED, or a wide band source such as an incandescent source together with appropriate narrow banding means, e.g., a filter), the output of 81 being coupled into a fiber comprising photorefractive modulator 80. The modulator is responsive to input signal 79, i.e., the amount of radiation transmitted through 80 and thence coupled into 74 varies in response to 79. The modulated cw signal arriving in 73 from 75 typically would be transformed into a standard pulsed signal and then be switched onto line 72 or onto another line 76. It will be understood that the depicted network is exemplary only, and that subscriber stations as described can be used with any fiber network geometry.

FIG. 8 schematically depicts an exemplary photorefractive modulator 80. The modulator comprises means for exposing a region of fiber 87 to spatially and temporally varying radiation. The means comprise a radiation source 82 whose output intensity is responsive to signal 79, and means 84 (e.g., a diffraction grating) for transforming output 83 of 82 into spatially varying radiation, with N maxima 851, 852,...85N. The core of fiber 87 contains an appr priate dopant (e.g., Bi), and

radiati n 83 is chosen t hav a wavelength that causes th dopant t underg a transiti n which results in a chang of the r fractiv ind x of th fiber core. Th transf rmed state advantage usly has a r lativ ly sh rt lifetime, such that modulation bandwidths of the order of 1 MHz can be achieved. The length of fiber 87 is coupled to conventional optical fiber (multimode or single mode) 10 and 10' by means of connectors 86, with cw radiation being introduced into 10'. If 83 is modulated temporally, then a temporally varying grating is formed in 87, causing coupling of a time-varying amount of radiation 88 from 87, and consequently amplitude modulation of the radiation in the fiber. For information on the photorefractive effect see, for instance, A. M. Glass, Optical Engineering, Vol. 17(5), pp. 470-479 (1978).

One of the advantages of the instant invention is that grating creation by axial distortion requires only such small deformations (typically < 0.5 µm) that fiber damage (including damage to the coating) is essentially nonexistent. Thus, it is possible to attach such couplers to fiber for indefinite periods of time.

Pseudo-periodic inventive couplers may be particularly advantageous for filtering applications, since such gratings can be designed to have substantially no attenuation for radiation outside a well-defined wavelength range. However, it is also possible to achieve effective filtering with periodic, even constant amplitude, gratings. For instance, we have achieved 15 dB excess attenuation at 1.5 µm, with 0.02 dB excess attenuation at 1.3 µm, with a constant amplitude
($N=60$, $\Lambda = 560$ µm) axial distortion grating.

In some circumstances, it may be desirable to provide means for enhancing the radiation of TL modes from the cladding of the single mode fiber. This can b achieved, for instance, by contacting the fiber with an

appropriate di lectric body at a downstream location, or by producing a macrobend in the fiber downstream from the grating. Such means are known in the art. See, for instance, U. S. Patents 3,931,518 and 4,135,780. Furthermore, it may be advantageous to use a corrugated body not only to produce the grating but also to perform an optical function, e.g., to change the shape of the emitted radiation pattern. Such corrugated transparent dielectric bodies are known (see, U. S. Patent 4,253,727).

Example 1: In commercially available single mode optical fiber (8.5 µm core diameter, 125 µm fiber diameter, dual polymer coating, diameter of coated fiber 245 µm, cut-off wavelength of LP_{11} 1.27µm) a grating was formed by squeezing an intermediate portion of the coated fiber between two corrugated PMMA members. The members were aligned such that valleys in one member were opposite peaks in the other member. Each corrugation had 10 periods, with a spacing of about 559 µm. A normal force of about 15 N was applied to the members, resulting in a deformation amplitude of about 0.2 µm. A commercially available 1.3 µm laser source was butt-coupled to one end of this optical fiber (to be referred to as the first fiber), the length of the transmission path between source and grating being about 1 km. A commercially available radiation detector was butt-coupled to a short length of single mode optical fiber of the above-described type (to be referred to as the second fiber), and the other end of the second fiber was placed at the focus of a graded index cylindrical lens of 2 mm diameter, with a normalized refractive index difference of about 0.04. The first fiber was mounted on a goniometer stage such that the center of the grating region was at the center of the circular measurement track along which a mounting platform could be moved. The lensed second optical fiber was attached t the platform, and th power f the laser radiation

that was emitted from the first fiber and c upled into the sec nd fiber was determined as a function f the angle Θ between the axis of the first fiber and the optical axis of the lensed second fiber. The maximum f detected power was about 18.5 dB below the power coupled into the first fiber, and occurred for Θ 20^{o}.

Example 2: In a set-up substantially as described above (except that detector and laser sourc were interchanged), the power that was emitted from the lensed second fiber and coupled into the first fiber by means of the grating was determined. The maximum detected power was about 18 dB below the power coupled into the second fiber, and occurred for Θ 20^{o}. Th small difference between the powers observed in Examples 1 and 2 is due to the variation in the efficiency of the connectors attached to source and detector, respectively.

As will be readily appreciated by those skilled in the art, the repeat distance $\Lambda(z)$ and amplitude function g(z) that are associated with a grating are nominal mathematical expressions, and that the actual repeat distance and amplitude of a grating in a fiber may depart from the nominal value, due to unavoidable manufacturing imperfections. However, typically it will be possible for actual repeat distances and amplitudes to be within $\pm$ 10%, preferably $\pm$ 5%, of their nominal values.

It will also be appreciated that, although in principle N, the number of elements in a grating, can be any integer greater than 1, typically N will be at least 5, frequently 10 or more.

Claims

1. Means for coupling electromagnetic radiation of wavelength λ_o into or from an intermediate portion of an optical fiber, the fiber comprising a core and a cladding surrounding the core and having optical characteristics including an attenuation constant α_{ij} and a propagation constant β_{ij} for each mode LP_{ij} of the radiation that can be present in the fiber, where i is a non-negative integer and j is a positive integer,

CHARACTERIZED IN THAT

a) the fiber is a single mode optical fiber at the wavelength λ_o;

b) the coupling means comprise means for forming in the intermediate portion of the fiber a "grating" consisting of N elements, a grating being a portion of fiber in which one or more fiber parameters are caused to vary as a function of the axial coordinat z of the fiber, the fiber parameters including the core refractive index and the fiber axis geometry, assciated with the grating being a nominal repeat distance $\Lambda(z)$ and a nominal amplitude function g(z);

c) $\Lambda(z)$ is chosen such that

$\Omega_o = (2\pi/\bar{\Lambda}) > \beta_{01} - 2\pi n_{cl}/\lambda_o$, where $\bar{\Lambda}$ is the average repeat spacing in the grating, β_{01} is the propagation constant of the LP_{01} mode of radiation, and n_{cl} is the refractive index of the cladding of the fiber;

d) $\Lambda(z)$ furthermore is chosen such that

$\Omega_o \quad \beta_{01} - \beta_{rs}$, where β_{rs} is the propagation constant of the LP_{rs} mode of radiation, where LP_{rs} is a tunneling leaky (TL) mode of the radiation of wavelength λ_o in the fiber; and

e) the attenuation constant α_{rs} of the LP_{rs} mode is less than about 1 dB/cm.

2. The coupling means of claim 1, wherein the means for forming a grating comprise means for impressing an undulation upon th fiber axis, or means for locally changing th core refractiv ind x.

3. Th c upling means of claim 1, wher in th LP_{rs} mod is th LP_{11} mode.

4. The coupling m ans of claim 1, wherein th nominal amplitude function g(z) is a constant.

5. The coupling means of claim 1, wherein the nominal amplitude function g(z) is proportional to a Gaussian function of z.

6. The coupling means of claim 1, wherein the nominal repeat distance $\Lambda(z)$ is a constant.

7. The coupling means of claim 2, wherein the means for impressing an undulation upon the fiber axis comprise at least one corrugated body, and means for urging the corrugated body against the fiber.

8. The coupling means of claim 2, wherein th means for locally changing the core refractive index comprise a photo-refractively active chemical element present in the core, and means for exposing the fiber core to actinic radiation, whereby the refractive index of the fiber core can be changed by means of the phot - refractive effect.

9. The coupling means of claim 2, wherein the means for locally changing the core refractive index comprise at least one corrugated body, and means for urging the corrugated body against the fiber, whereby the refractive index of the fiber core can be changed by means of the photo-elastic effect.

10. The coupling means of claim 1, wherein at least the intermediate portion of the fiber is coated with a material that is substantially transparent for the electromagnetic radiation of wavelength λ_0.

11. The coupling means of claim 2, further comprising means for enhancing the emission of radiation from the cladding of the fiber.

12. The coupling means of claim 11, wherein the means for enhancing emission of radiation from the cladding comprise a dielectric body contacting the fiber d wnstream from th grating, the di lectric b dy being

substantially transparent for th radiati n of wavelength λ_o.

13. The coupling means of claim 11, wherein the means for enhancing emission of radiation from the cladding comprise means for introducing a macrobend in the fiber downstream from the grating.

14. An optical communications system comprising a source of first electromagnetic radiation of wavelength λ_o, an optical fiber adapted for guiding the first radiation, first means for coupling the first radiation into the fiber at a first fiber location, and means for detecting, at a second fiber location spaced apart from the first fiber location, the first radiation that is transmitted from the first to the second fiber location through the fiber, the fiber comprising a core and a cladding surrounding the core, the fiber having optical characteristics including an attenuation constant α_{ij} and a propagation constant β_{ij} for each mode LP_{ij} of the first radiation that can be present in the fiber, where *i* is a non-negative integer and *j* is a positive integer, the optical communications system further comprising second means for coupling first radiation into or from the fiber at a third fiber location intermediate the first and the second fiber locations without breaking or terminating the fiber,

CHARACTERIZED IN THAT

a) the fiber is a single mode optical fiber at the wavelength λ_o;

b) the second means comprise means for forming in the intermediate portion of the fiber a "grating" consisting of N elements, a grating being a portion of fiber in which one or more fiber parameters have a regular variation as a function of the axial coordinate *z* of the fiber, the fiber parameters including the core refractive index and the fiber axis geometry, associated with the grating being a nominal repeat distance $\Lambda(z)$ and a nominal amplitude function $g(z)$;

c) $\Lambda(z)$ is chos n such that

$\Omega_o = 2\pi/\Lambda > \beta_{01} - 2\pi n_{cl}/\lambda_o$, wher Λ is th av rag repeat spacing in the grating, β_{01} is the propagation constant of the LP_{01} mode of radiation, and n_{cl} is the refractive index of the cladding of the fiber;

d) $\Lambda(z)$ furthermore is chosen such that

Ω_o $\beta_{01} - \beta_{rs}$, where β_{rs} is the propagation constant of the LP_{rs} mode of radiation, and where LP_{rs} is a tunneling leaky (TL) mode of the radiation of wavelength λ_o in the fiber; and

e) the attenuation constant α_{rs} of the LP_{rs} mode is less than about 1 dB/cm.

15. Communications system of claim 14, wherein the second means form a variable attenuator.

16. Communications system of claim 14, wherein the second means comprise clamp-on means comprising corrugated means for forming the grating in the fiber, means for urging the corrugated means against the fiber, and means for detecting the first radiation emitted from the fiber at the third fiber location.

17. Communications system of claim 14, wherein the source of electromagnetic radiation also emits electromagnetic radiation of wavelength other than λ_o, wherein the first means are adapted for coupling at least some of the radiation of wavelength other than λ_o into the fiber at the first fiber location, and wherein the second means form a filter adapted for selectively coupling at least some of the first radiation from the fiber.

18. An optical fiber communications system comprising

a) at least a first and a second terminal station, the first terminal station comprising means for generating an optical signal, and the second terminal station comprising means for receiving the optical signal;

b) signal distributi n means;

c) a first optical fiber transmission channel adapted for transmitting the optical signal from the first terminal station to the signal distribution means;

d) means for coupling optical radiation into the first optical fiber transmission channel at the first terminal station;

e) a second optical fiber transmission channel adapted for transmitting the optical signal from the signal distribution means to the second terminal station;

CHARACTERIZED IN THAT the means for generating the optical signal comprise

f) a source of cw (continuous wave) optical radiation of substantially constant amplitude comprising radiation of wavelength λ_o, the means of d) serving to couple the cw optical radiation into the first optical fiber transmission channel;

g) first means for coupling optical radiation of wavelength λ_o from an intermediate portion of the first optical fiber transmission channel, at least the intermediate portion of the first optical fiber transmission channel comprising a length of optical fiber containing a photorefractively active element; the first means comprising

i) means for generating actinic radiation;

ii) means for illuminating at least part of the length of optical fiber with the actinic radiation such that the intensity of the actinic radiation has N periodically or pseudo-periodically spaced maxima in the part of the length of optical fiber, where N is an integer greater than 1; and

iii) means for changing the intensity of the actinic radiation in response to an electrical signal provided to th first means, whereby the refractive ind x f the ptical fiber in the part f the

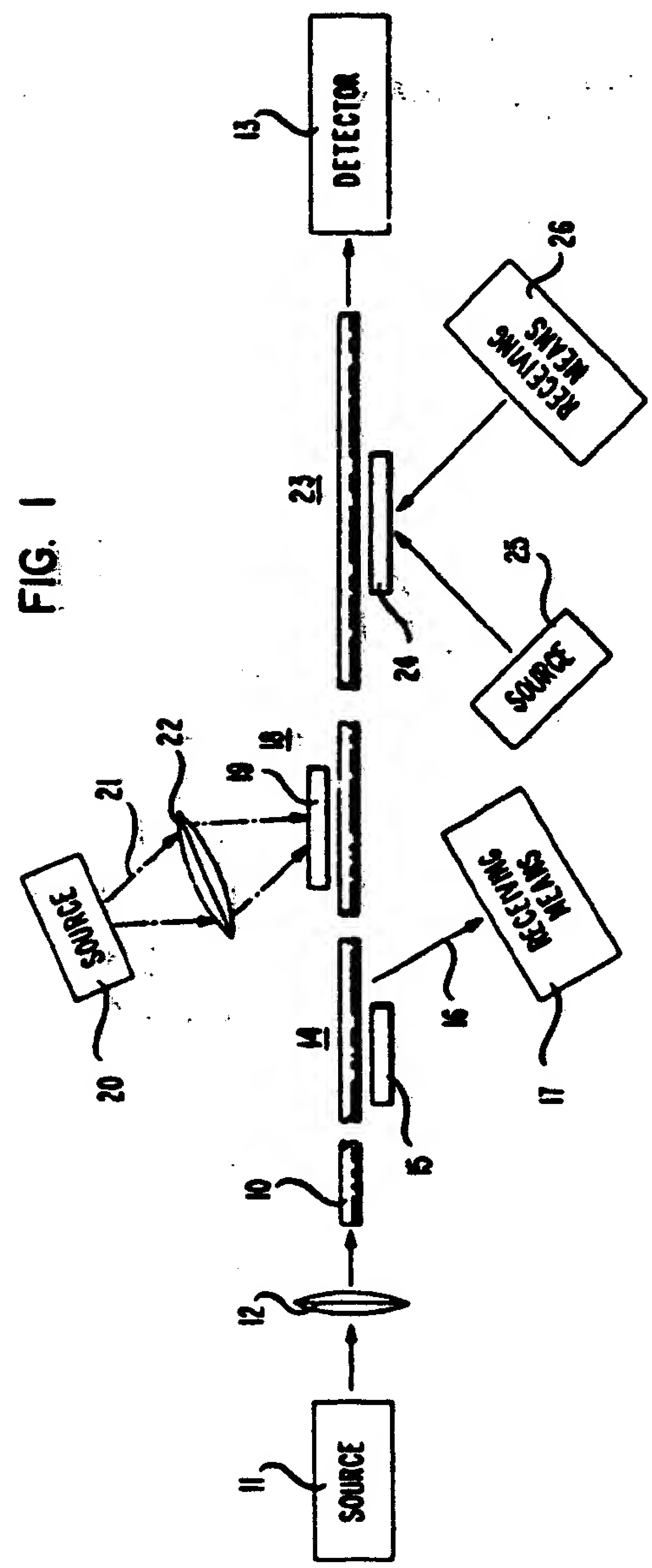
length of optical fib r is varied ph torefractiv ly, and whereby the intensity of the ptical radiation f wavelength λ_0 in the optical fiber is varied in response to the electrical signal.

19. Communications system of claim 18, wherein the signal distribution means comprise a multiplicity of signal switching stations, each one of the signal switching stations being connected, by means of optical fiber transmission channels, to at least one other signal switching station.

20. Communications system of claim 19, wherein the first terminal station further comprises means for receiving an optical signal, the second terminal station further comprises means for generating an optical signal, and the first and second optical fiber transmission channels being adapted for transmitting optical signals to and from the first and second terminal stations, respectively.

21. Communications system of claim 18, wherein the photorefractively active element is selected from the group consisting of Fe and Bi.

FIG. 1


SOURCE
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12
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RECEIVING MEANS
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RECEIVING MEANS
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DETECTOR
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FIG. 2

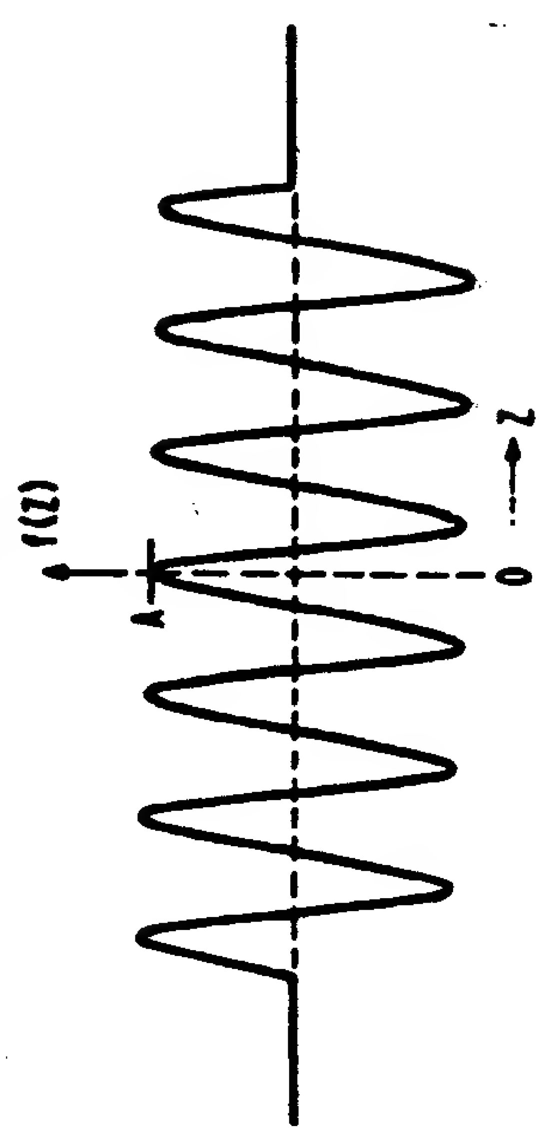
f(Z)
A
0
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FIG. 3

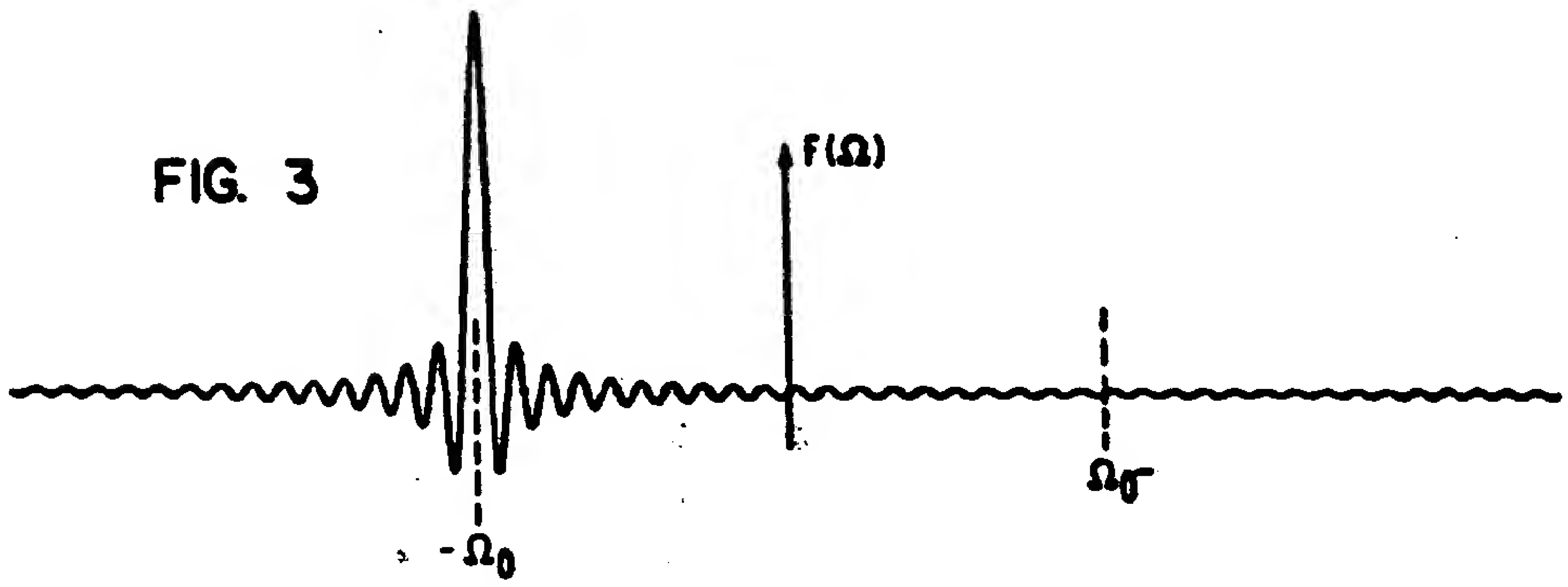


FIG. 4

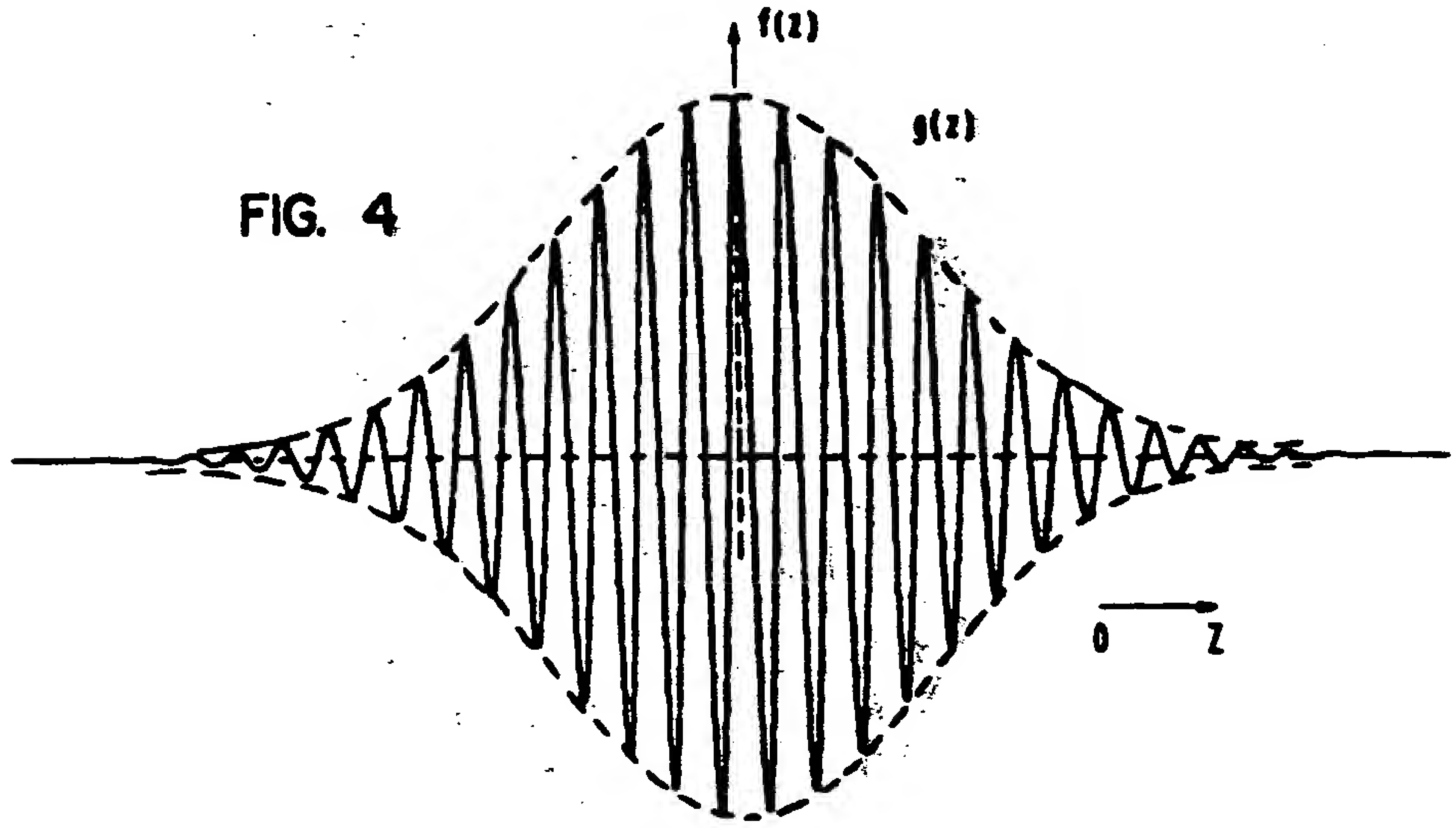


FIG. 5

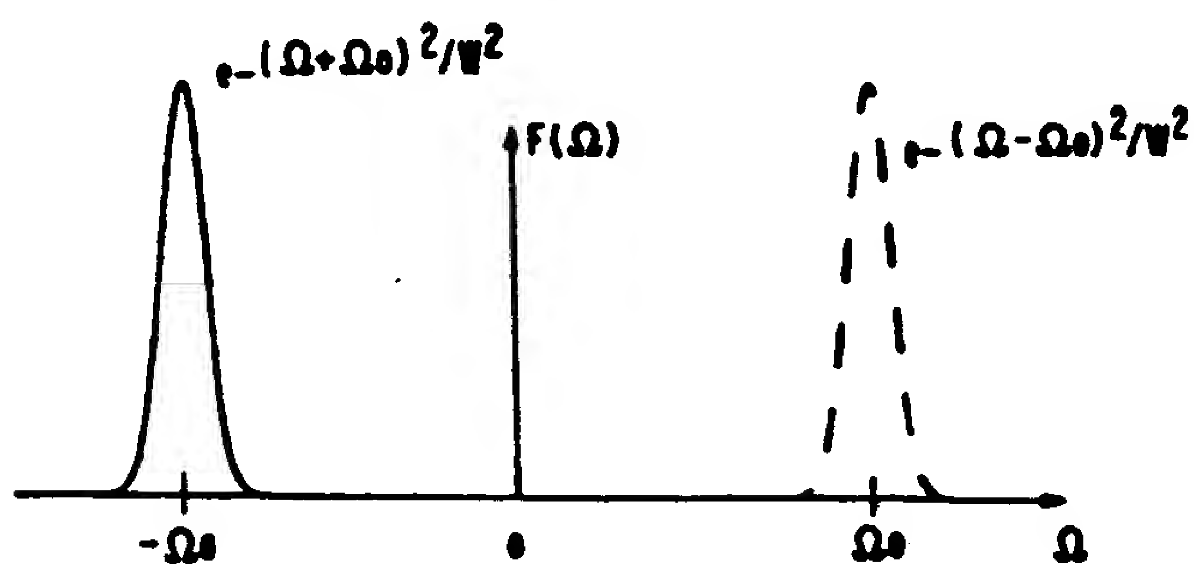


FIG. 6

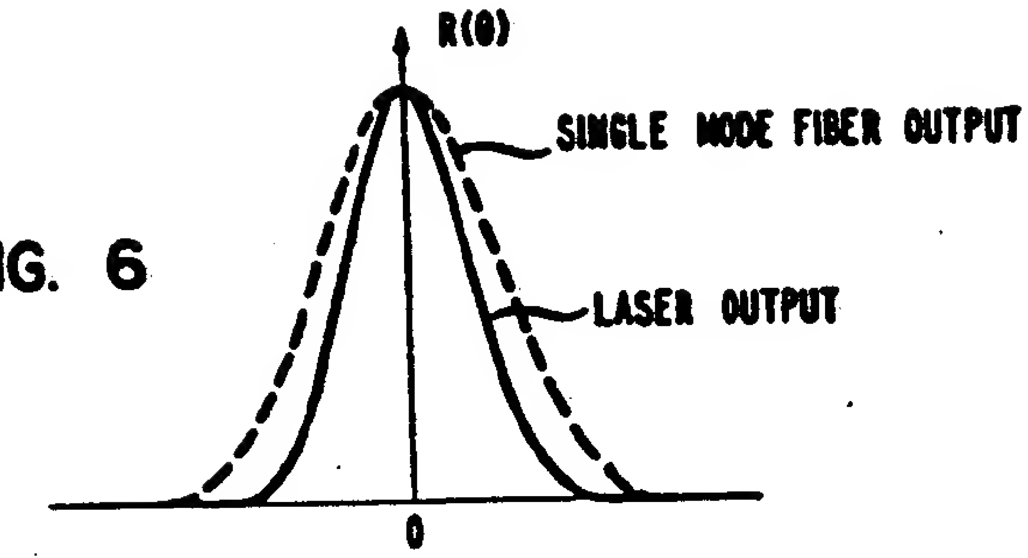


FIG. 7

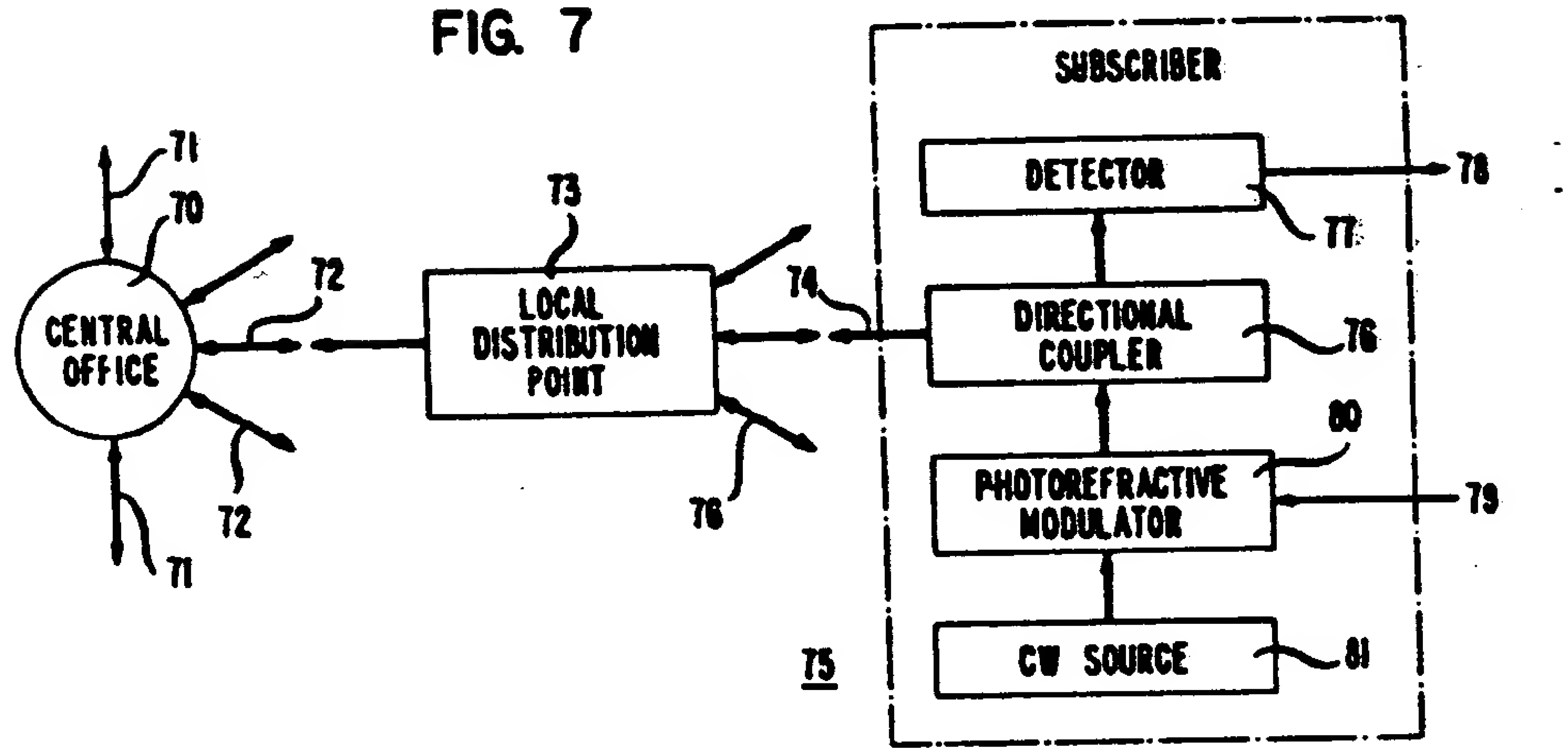
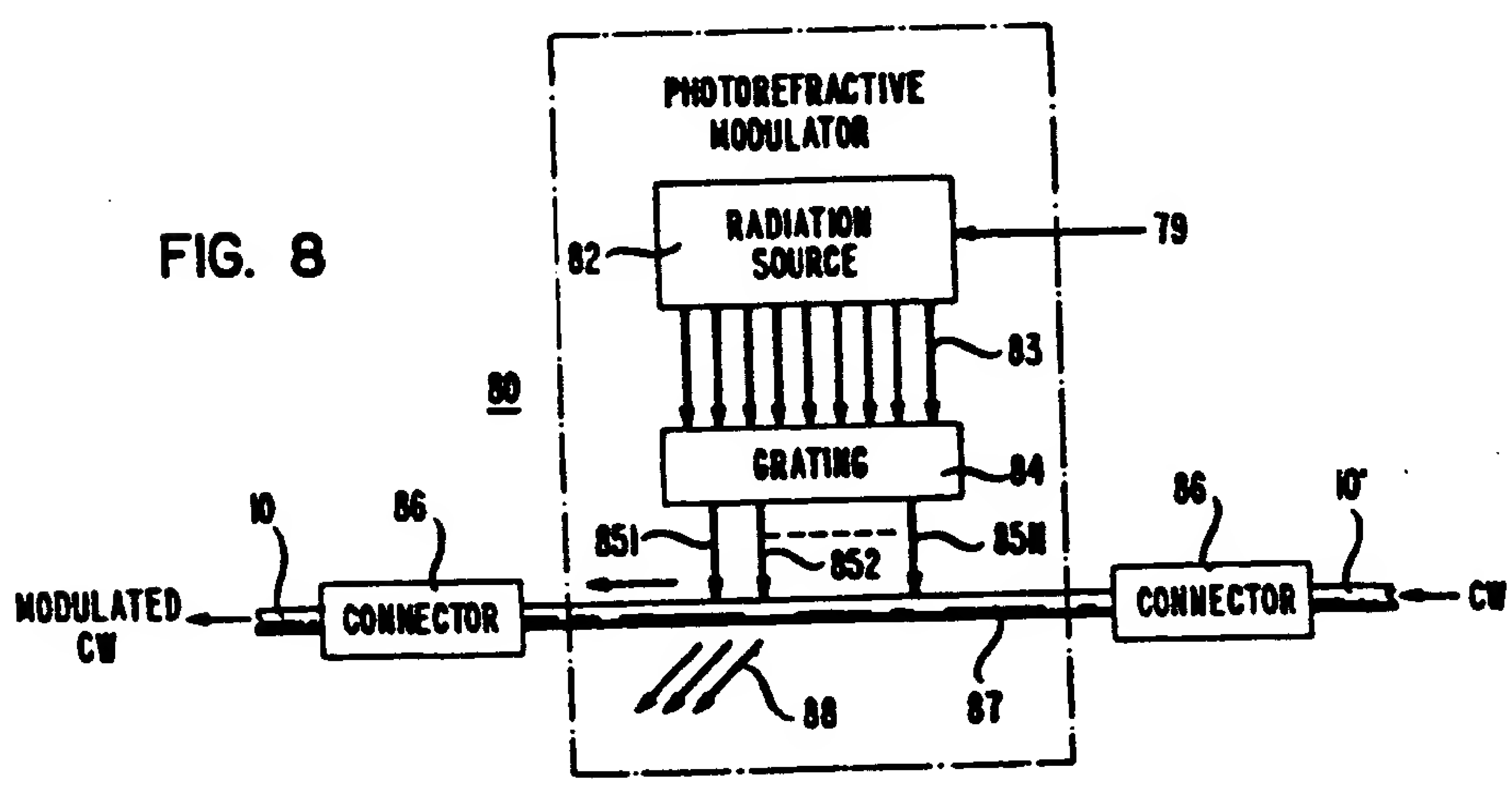


FIG. 8



(19) Europäisches Patentamt
Eur pean Patent Office
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(11) Publication number: 0 221 560
A3

(12) **EUROPEAN PATENT APPLICATION**

(21) Application number: 86115406.0

(22) Date of filing: 06.11.86

(51) Int. Cl.[3]: H 04 B 9/00
G 02 B 6/34, G 02 F 1/01

(30) Priority: 06.11.85 US 795482

(43) Date of publication of application: 13.05.87 Bulletin 87/20

(88) Date of deferred publication of search report: 13.09.89

(84) Designated Contracting States: DE FR GB NL SE

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(54) **Coupling device for single mode optical fiber and communications system comprising same.**

(57) Optical radiation can be efficiently removed from, or injected into, single mode optical fiber at an intermediate point along the fiber, by causing quasi-resonant coupling of the guided mode LP_{01} to an appropriate tunneling leaky (TL) mode, e.g., LP_{11}. Such coupling is caused by means of a "grating" in the fiber, being formed by different methods.

The nominal grating spacing $\Lambda(z)$ is chosen such that $\Omega_o = (2\pi/\overline{\Lambda}) > \beta_{01}-2\pi n_{cl}/\lambda_o$, where $\overline{\Lambda}$ is the average grating spacing, β_{01} is the propagation constant of the LP_{01} mode, n_{cl} is the refractive index of the fiber cladding, and λ_o is the wavelength of the radiation to be coupled from or into the fiber. Furthermore, $\Lambda(z)$ is to be chosen such that $\Omega_o = \beta_{01} - \beta_{rs}$, where β_{rs} is the propagation constant of the selected TL mode. In order for the coupling to be quasi-resonant, it is necessary that α_{rs}, the attenuation constant of the selected TL mode, be relatively small, typically < 1 dB/cm. By appropriately choosing $\Lambda(z)$ and/or the amplitude function of the grating, it is still possible to further increase the coupling efficiency.

Devices according to the invention can be advantageously used not only as radiation couplers but also as filters and, if they are of the photorefractive type, as amplitude modulators.

EP 0 221 560 A3

European Patent Office

EUROPEAN SEARCH REPORT

0221560
Application Number

EP 86 11 5406

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl. 4)
A	US-A-3 916 182 (DABBY) * Abstract; column 3, lines 21-30; column 4, lines 41-54; column 5, lines 13-26; claims 34,35 * ---	1,2,8,9,14,15	H 04 B 9/00 G 02 B 6/34 G 02 F 1/01
A	DE-A-2 654 085 (COMPAGNIE GENERALE D'ELECTRICITE S.A.) * Page 4, paragraph 3; page 7, paragraph 3; figure 1 * ---	1,2,4,6,7,10-12	
A,D	US-A-3 931 518 (MILLER) * Figure 2; abstract * ---	1,2,4,6,7,10-12	
A	PATENT ABSTRACTS OF JAPAN, vol. 7, no. 239 (E-206([1384], 25th October 1983; & JP-A-58 129 848 (NIPPON DENSHIN DENWA KOSHA) 03-08-1983 * Abstract * ---	1,2,14-16	
A	IEE PROCEEDINGS SECTION A à I, vol. 132, no. 5, part J, October 1985, pages 277-286, Stevenage, Herts, GB; R.C. YOUNGQUIST et al.: "All-fibre components using periodic coupling" * Page 281, column 2, paragraph 2 - page 282, column 1, paragraph 1 * -----	18	TECHNICAL FIELDS SEARCHED (Int. Cl.4) H 04 B G 02 B G 02 F

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	16-06-1989	SCRIVEN P.

CATEGORY OF CITED DOCUMENTS

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T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
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EPO FORM 1503 03.82 (P0401)

(PCT.202) 8030 Electronics Letters
32(1996) 26 September, No. 20, Stevenage, Herts, GB

Tunabl fibre bandpass filter based on a linearly chirped fibr Bragg grating for wav length d multipl xing

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E p.1918-1919 (2) p.d. 26-09-1996

Indexing terms: Gratings in fibres, Optical fibre filters

A novel tunable fibre bandpass filter based on a linearly chirped fibre Bragg grating (LCFBG) has been demonstrated. The transmission peaks in the LCFBG stopband are electronically induced by controlling the strain distribution along the LCFBG using a piezoelectric stack. Transmission peaks with 0.58nm bandwidth and 10.6dB rejection ratio have been achieved with a tuning step of 0.28nm over a range of 10nm.

Introduction: The phase-shifted fibre Bragg grating (FBG) is showing promise as an adaptable high finesse transmission filter or switching element for future dense WDM optical communication systems [1]. To date, two techniques for fabricating phase-shifted FBGS have been reported: the phase-shifted phase mask technique [2] and the UV post-processing method [3]. However, high quality phase masks are very expensive and UV post-processing requires tight control of precision, especially in short gratings, and all have limitations when it is desirable to tune the bandpass peak or to provide a wider bandpass peak and rejection band. In this Letter we present a new, yet simple, method for introducing bandpass peaks inside the stopband of an LCFBG, by controlling the strain distribution along the LCFBG. As a result of this arrangement, not only can the bandpass peak be made tunable, but multi-bandpass peaks can also be opened simultaneously.

Principle: Theoretically it has been shown [1] that the introduction of a $\pi/2$ phase-shift at the centre of a uniform (i.e. unchirped) FBG opens a 100% transmission peak within the stopband. The peak shifts either with the amount of phase-shift at the centre location or with the locations of the $\pi/2$ phase-shift. While in principle a broader stopband for a uniform FBG can be achieved using short structures, it could be difficult in the FBG fabrication. Instead, in our scheme we use an LCFBG to increase the stopband.

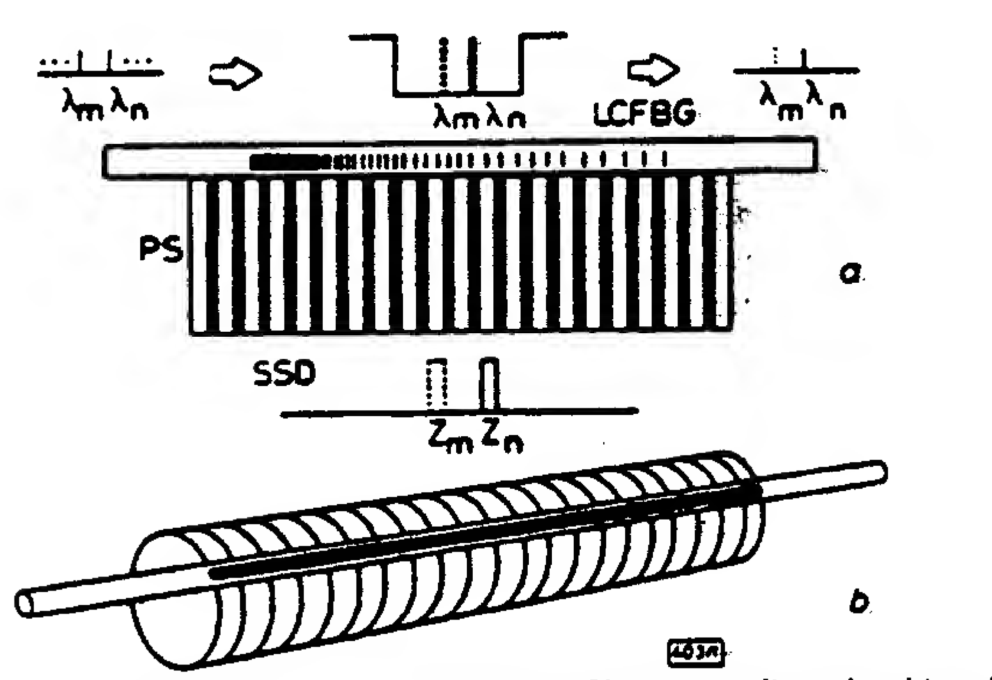

Fig. 1 *Schematic diagram of tunable fibre filter using linearly chirped fibre Bragg grating (LCFBG)*

a Operating principle: bandpass peak varies with location of strain step applied
PS: piezoelectric stack
SSD: strain step distribution
b Perspective view of tunable filter configuration

We assume that an LCFBG with length L can be divided into many grating segments L_i, each of which covers a multiple number of pitches. As an LCFBG reflects different wavelengths at different locations along its length, it satisfies the Bragg condition for a range of wavelengths. Hence when a grating segment is uniformly strained in tension, each wavelength component contributed by the corresponding pitches of that grating segment will be red-shifted, resulting in a transmission peak due to the depletion centred at λ_0. Therefore the peak λ_0 will shift with the location f the grating segment strained, and multiple bandpass peaks within the stopband will occur when multiple segments are strained simultaneously. The magnitude and spectral width of this peak depend on the strain level applied, the length of the grating segment, the chirped rate of the LCFBG, and the grating strength kL.

Experiment and discussion: Fig. 1*a* and *b* depict the tunable fibre filter, where an LCFBG was bonded ont the surface of a segmented piezoelectric stack. A 35mm LCFBG with a reflectivity of 99%, FWHM bandwidth of 13nm, and chirp rate of 0.12nm/mm was used. The 45mm long piezoelectric stack consists of 21 active segments (each ~1.4mm in thickness), with an inactive isolation of ~0.56mm between segments. Each segment can be excited independently, allowing quasi-independent strain control of each segment [4]. Some mechanical coupling between the segments takes place due to the rigidity of the bonding agent. The attached grating experiences the imposed strain distribution and its characteristics can therefore be precisely controlled. The transmission spectrum was obtained by scanning a tunable laser (Intun-1500) with a resolution of 0.01nm, and monitoring the transmitted power.

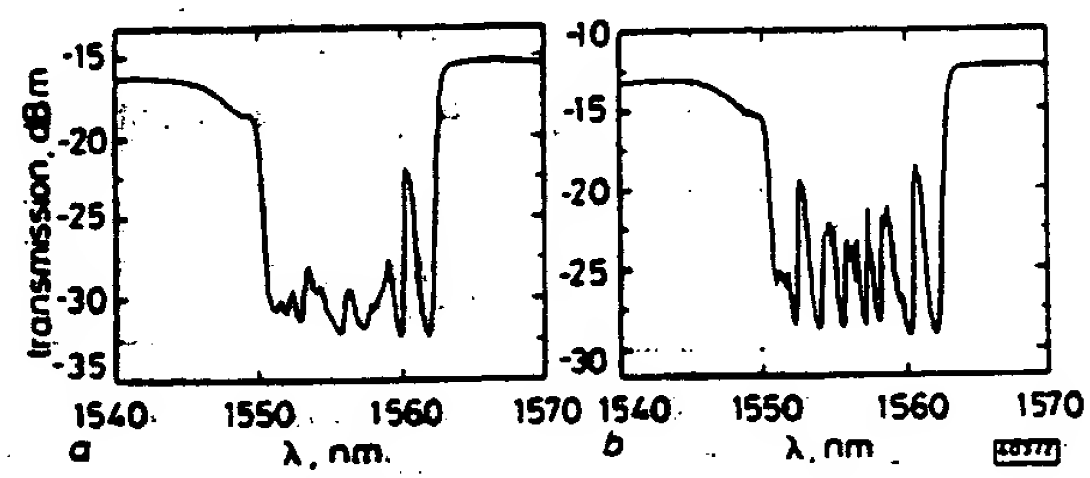

Fig. 2 *High resolution measurement (0.01nm step size) of filter transmission spectral response*

a Single bandpass peak induced with strain step 1/5 distance from one end of LCFBG
b Comb filtering response with multiple strain steps induced at different locations along LCFBG simultaneously

When a single grating segment was strained with a strain step 1/5 of the distance from one end of the LCFBG, a narrow transmission peak opened in the LCFBG stopband, as shown in Fig. 2*a*. In this case, a filter bandwidth of 0.58nm with 10.6dB contrast ratio was achieved. When the location of the strained grating segment was altered, the peak shifted accordingly as predicted (typically 25ms setting time). In fact a tuning step of 0.28nm was achieved, limited by the spatial resolution of the stack. Fig. 2*b* shows a comb filtering response when multiple grating segments were strained simultaneously. This means that by properly controlling the strain distribution, synthesis of various filter responses would also be possible [5]. Another attractive feature is that the number of channels that can be demultiplexed increases with the stopband of the grating. By appropriately designing the LCFBG and piezoelectric stack, the potential demultiplexing capability can be expected to be high. The loss in transmission shown in Fig. 2 was mainly caused by the maximum strain level applied to each grating segment being limited to ~500με for the current stack. In addition, owing to the effect of the interaction between the active segments of the piezoelectric stack when strained, the quantitative description of the relative phase change at each grating segment becomes more complicated. A more in-depth analysis of these effects is beyond the scope of this Letter.

Conclusion: We have demonstrated an attractive method for constructing a tunable fibre transmission filter by controlling the strain distribution along an LCFBG using a piezoelectric stack. Multiple bandpass peaks can also be introduced to provide other devices such as comb filters. This offers considerable potential for the WDM applications as a real-time channel filtering/switching element. Work is being directed towards improving the tuning steps and the loss in the bandpass peaks, as well as extending the tunable range.

IEE 1996 *12 August 1996*
Electronics Letters Online No: 19961242

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Ag^+-Na^+ exchanged waveguides from molten salts in a chemically durable phosphate glass

L.C. Barbosa, N. Aranha, O.L. Alves and R. Srivastava

Indexing terms: Ion exchange, Optical waveguides, Waveguide lasers

The authors report that Ag^+-Na^+ ion exchange has been performed for the first time from molten salt baths in a chemically durable phosphate glass. Characterisation of planar waveguides, fabricated at different temperatures, diffusion times and with varying melt concentrations, indicates large diffusion coefficients and higher index changes with no deterioration of surface quality.

Introduction: Ion exchanged glass waveguides play an important role as passive devices in optical communications [1] and sensors [2], and as active devices in all optical switching [3] and waveguide lasers [4]. In fact, the best figure of merit for nonlinear optical switching requires Kerr-type nonlinearity available in large refractive index glasses [5]. On the other hand, compared to silicate glasses, phosphate glasses are better suited for rare-earth doped glass laser media because of their favourable thermal and spectroscopic properties, even at higher rare-earth ion concentrations [6].

There have been several reports of fabrication of waveguides in rare-earth doped phosphate glasses. The first such report [4] deals with a dry diffusion process where an electric field assisted ion-exchange from a silver stripe was performed in a commercial Nd^{3+}-doped phophate glass (Hoya, LHG-5). The dry process was preferred because most phosphate glasses are known to be prone to chemical attack by molten salts. Recently, interest has shifted towards special compositions of phosphate glasses for ion exchange from molten salts [7, 8]. In [7], K^+-Na^+ exchanged channel waveguides were fabricated from a KNO_3 melt. No information however was given regarding the diffusion rate, index increase, etc. Moreover, it was reported that the process caused a 0.8µm deep depression in the exchanged region of the glass surface, which is an obvious cause of scattering losses. In [8], two-step ion exchange was used in a special glass but no details about the ion pair or exchange process parameters were given. Finally, Ag^+-Na^+ exchange from molten salts in phosphate glasses has not yet been reported.

Recently, the synthesis of a new phosphate glass with much better chemical durability was reported [9, 10]. The glass consists of a mixture of oxides of phosphorus, niobium, lead and sodium. Niobium was added for chemical durability and lead was used to increase the linear refractive index (n = 1.775). The glass fabrication details along with the chemical durability and optical characterisation studies are reported elsewhere [9, 10]. The glass has a transition temperature of Tg 570°C and shows high solubility for rare-earth ions. We have been able to dope this glass with up to 2% by weight of Er_2O_3 without any difficulty. In this Letter, we report the fabrication of waveguides using this phosphate glass, along with a detailed study of the dependence of the waveguide parameters on processing.

Experiment: Planar waveguides were fabricated by immersing polished glass substrates, typically 20mm × 10mm × 1mm in dimensions, in a molten salt bath of equal molar fractions of $NaNO_3$ and KNO_3. This mixture allows ion exchange at temperatures as low as 250°C. The molar fraction of $AgNO_3$ was varied from 0.1 to 5%. The salt was contained in a silica crucible held in a vertical furnace, in which the temperature was controlled to within ±1°C. The sample holder, also made of silica, was attached to a motorised system via a shaft which gradually lowered the sample holder into the salt bath. Ion exchange was performed at three temperatures: 255, 305 and 355°C; and exchange times were 30, 60 and 90 min, respectively. In each ease, at least three guided modes were observed in the prism coupler at the wavelength of 632.8nm. This was adequate for determination of the index profile using the InWKB method [11]. No attempt was made to fit the mode index data to any analytical function for the index profile. The surface index change (Δn) and the effective profile depth (d) were estimated as follows:

Δn = difference in the mode-index of the fundamental mode and the substrate index

d = the depth where the index increase reduces to l/e of its value at the surface.

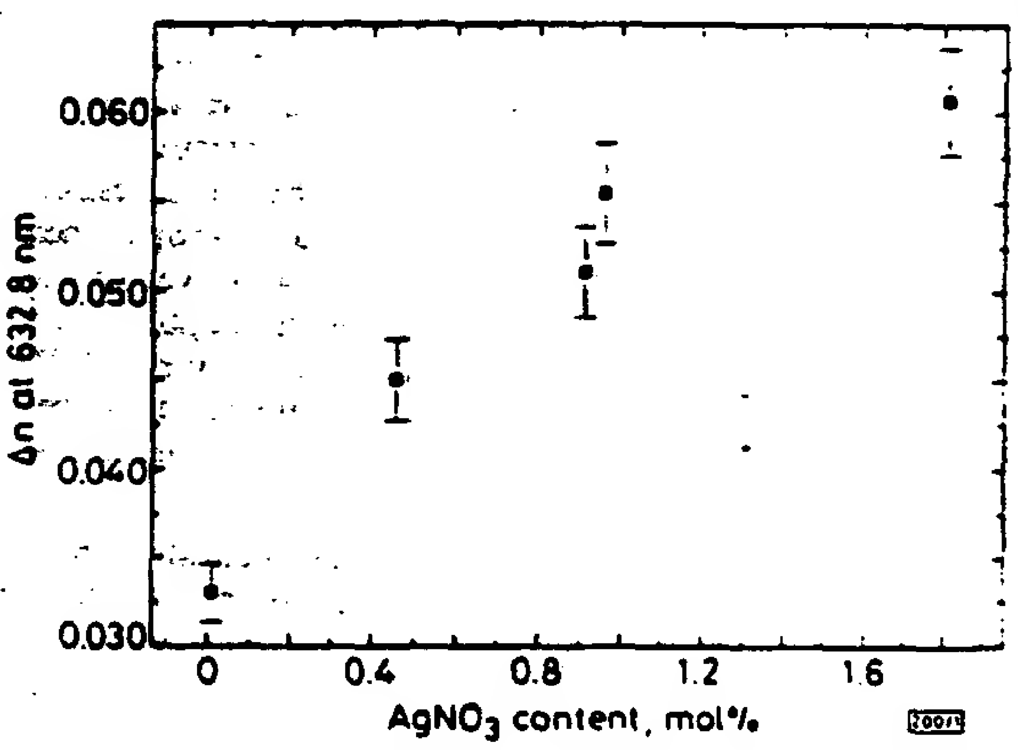

Fig. 1 *Surface index change against the molar concentration of $AgNO_3$ in melt at 355°C*

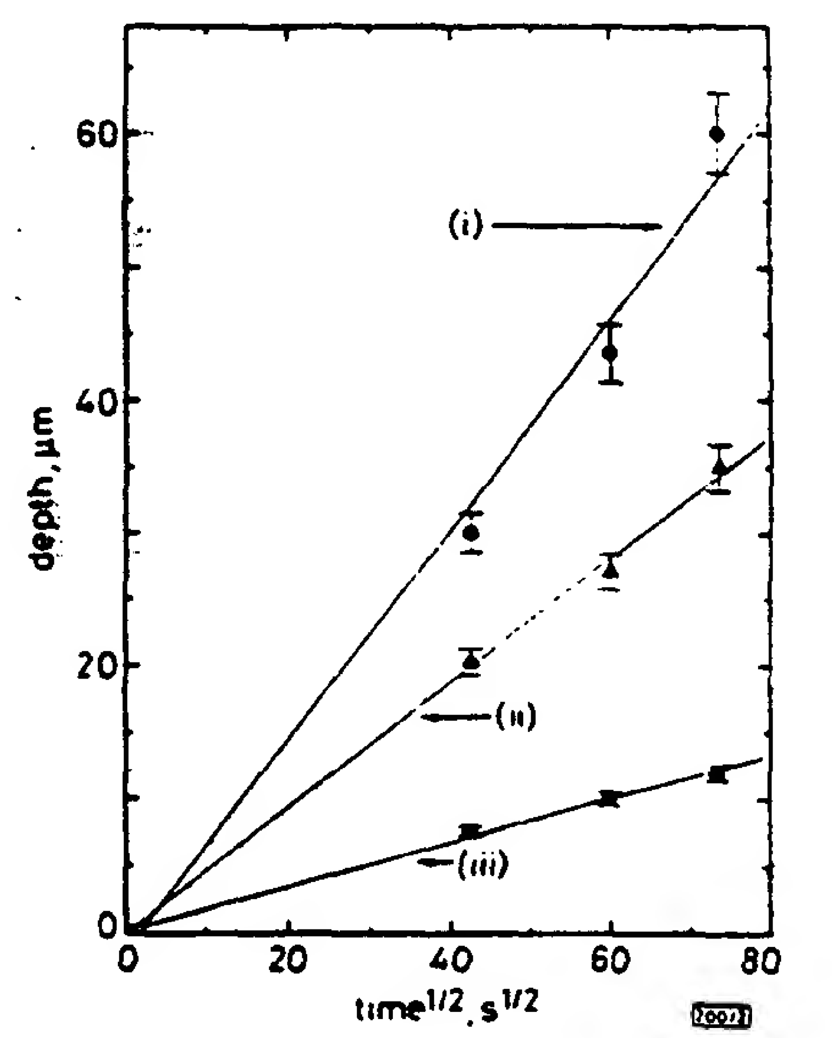

Fig. 2 *Waveguide depth against square-root of time*

For molten bath with 0.5 mol% of $AgNO_3$ content
Effective diffusion coefficients are also shown
(i) $D = 6.19 \times 10^{-13} m^2/s$
(ii) 2.19×10^{-13}
(iii) 3.06×10^{-14}
■ 255°C
▲ 305°C
355°C